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CLUSTERING AND COLOUR PREVIEW OF POLARIZATION-ENCODED IMAGES

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ABSTRACT

In the framework of Stokes parameters imaging, polarization-encoded images have four channels which make physical interpretation of such multidimensional structures hard to grasp at once. Furthermore, the information content is intricately combined in the parameters channels which involve the need for a proper tool that allows the analysis and understanding of polarization-encoded images. In this paper we address the problem of analyzing polarization encoded images and explore the potential of this information for classification issues and propose ad hoc colour display as an aid to the interpretation of physical properties content. We propose a novel mapping between the Stokes space and a parametric HSV colour space.

1. INTRODUCTION

Classical imaging systems based on light intensity measurements suffer from several limitations inherently related to the omission of the vector nature of light [1]. These restrictions become critical for bad light illuminations, transparent objects or bright reflections toward the detector (CCD camera) by metallic edges for example. In order to get around these limits, making the most of light polarization has shown to be a useful and powerful technique. It has become gradually clear that the polarization properties of any target provide a rich set of information about the local nature of the target. Indeed, the partially polarized nature of light is of prime importance while incoming radiation interacts with objects. This aspect seems to have been largely not utilized in active imaging systems in the visible wavelengths domain [2].

Polarization imaging consists of the distributed measurements of polarization parameters of light across a scene. That way, we define the "Stokes imaging" as the bidimensional measurements of light's Stokes parameters impinging on the CCD camera. Accordingly, Stokes images have multidimensional structure, i.e. multi-component information is attached to each pixel in the image [3]. In this paper we propose a novel mapping between the Stokes space and a parametric colour space where an adequate distance can be defined and used in the fuzzy C-means clustering algorithm for classification issues [4], [5], [6]. The segmentation map is used as a priori information in order to allow the best distribution of the information in the colour space. The use of the RGB (Red, Green, and Blue) colour space is not straightforward, so we chose to use the HSV (Hue, Saturation, Value) one which is well suited for describing colours in terms that are practical for a better physical interpretation. Histogram equalization is applied also to each class of the channel associated to the brightness axis in order to preserve the information in the intra-class smooth variations. The proposed algorithm is applied and validated with Stokes images of biological tissues: histological section of a red picosirus died bone and a histological section of a healthy vessel.

2. BACKGROUND

2.1 HSV colour space

HSV colour space offer intuitive handling of colours. It decouples the intensity component from the colour-carrying information (hue and saturation) [7]. Each colour is described according to three physiological criterions:

- The hue (H) is related to the colour perception, it describes the colour purity $0 \le H \le 360°$.
- The saturation (S) gives a measure of the degree to which a pure colour is diluted by white light $0 \le S \le 1$.
- The brightness (V) is an achromatic information and gives a measure of the light quantity in the colour (bright to dark) $0 \le V \le 1$.

These three components can be represented in polar coordinates by a cone where the set of all reachable colours are synthesized. Figure (1); shows the cone that corresponds to the HSV model.

The main advantage of this model comes from the fact that each component can be related to a physical quantity that can be interpreted visually. In this way, the variations of the physical quantity related to channel V in the image are represented by variations in pixel's brightness.

The HSV colour space can also be visualized in cylindrical coordinates in a similar way to the conical representation of Figure (1), the hue varies along the outer circumference of a cylinder, while saturation is given by the distance to the center of a circular cross-section.

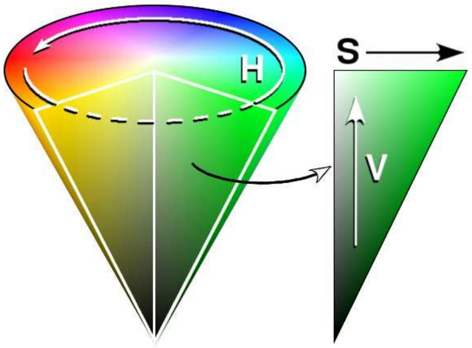

Figure 1 – Conical representation of the HSV colour space

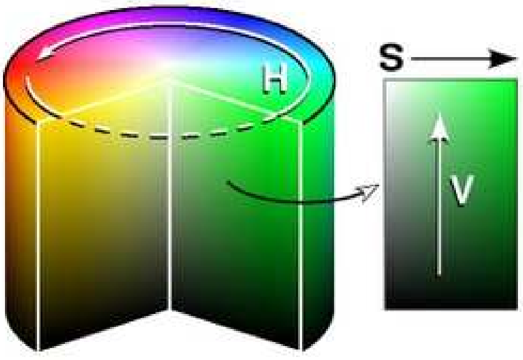

Figure 2 – The HSV colour space in cylindrical coordinates

Brightness again varies from top to bottom as exemplified in Figure (2). Such a representation might be considered the most mathematically accurate model of the HSV colour space; however, in practice the number of visually distinct saturation levels and hues decreases as the value approaches black. Additionally, computers typically store RGB values with a limited range of precision; the constraints of precision, coupled with the limitations of human colour perception, make the cone visualization more practical in most cases.

2.2 Stokes imaging

The design of imaging systems, that can measure the polarization state of the outcoming light across a scene, is mainly based on the ability to build effective Polarization State Analyzers (PSA) in front of the camera that permit to acquire the Stokes vectors corresponding to each pixel in the image. It can be shown that four intensity measurements are needed in order to obtain the Stokes image, the reader is referred to [3]
for more details.

The general polarization state of a light wave can be described by the so called “Stokes vector” (SV) **S** which fully characterizes the time-averaged polarization properties of radiation. It is defined by the following combination of complex-valued components E_x and E_y of the electric vector [8] in two mutually orthogonal directions x and y as

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{bmatrix} \langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle \\ \langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle \\ 2\,\mathrm{Re}\left(\langle E_x^* E_y \rangle\right) \\ 2\,\mathrm{Im}\left(\langle E_x^* E_y \rangle\right) \end{bmatrix} \tag{1}$$

where S_0 defines the total intensity, S_1 describes the excess of parallel to perpendicularly polarized light, and S_2 and S_3 convey the nature and handedness, respectively, of the wave. It is straightforward to show that

$$S_0^2 \geq S_1^2 + S_2^2 + S_3^2 \tag{2}$$

where the equality holds for completely polarized radiation. We note further that the geometrical polarization parameters of the wave [9], i.e., degree of polarization ($0 \leq DOP \leq 1$), orientation $(-\pi/2 \leq \lambda < \pi/2)$, and ellipticity $(-\pi/4 \leq \varepsilon \leq \pi/4)$, can be expressed in terms of S_0, S_1, S_2, and S_3 [8], [10] as follows

$$\begin{aligned} DOP &= \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \\ \lambda &= 0.5\tan^{-1}\left(\frac{S_2}{S_1}\right) \\ \varepsilon &= 0.5\sin^{-1}\left(\frac{S_3}{\sqrt{S_1^2 + S_2^2 + S_3^2}}\right) \end{aligned} \tag{3}$$

It can be shown that the normalized Stokes vector $\mathbf{S}/S_0$, defines a single point that lies in a unit ball called the Poincaré ball as depicted in Figure (3).

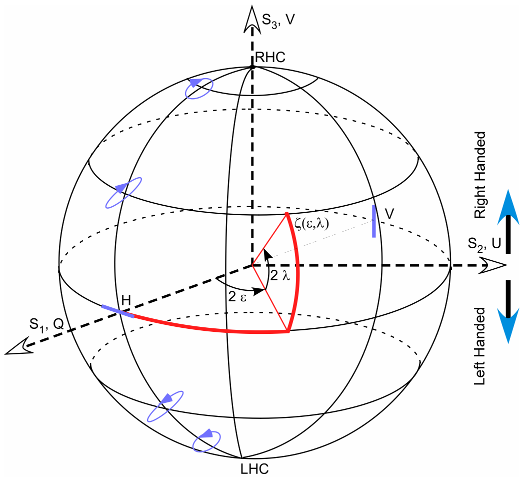

Figure 3 – The Poincaré ball. Completely polarized states lie on the surface of the sphere. Partially polarized radiations lie inside the ball.

Figures (4a-4d) and Figures (5a-5d) represent respectively the four Stokes channels images of a histological section of a bone coloured with red picosirius imaged at 650 nm wavelengths, and of a healthy vessel. The image at the upper left in the two cases corresponds to conventional intensity image.

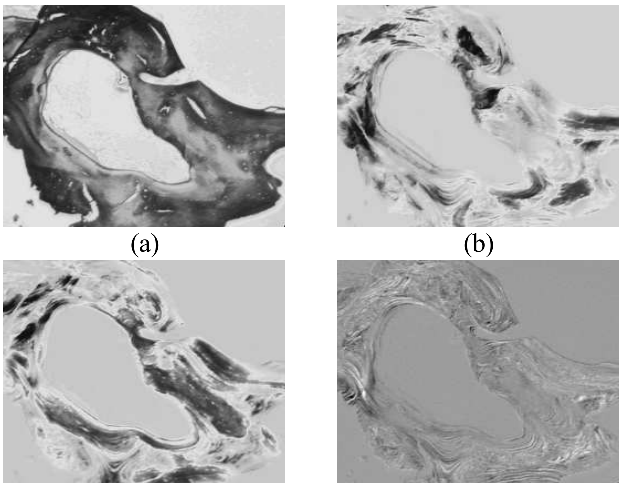
(a) (b)
(c) (d)

Figure 4 – S_0 (a), S_1 (b), S_2(c), and S_3 (d) images of a histological section of a bone died with red picosirius and imaged at 650 nm wavelength. The image at the upper left is to be compared with a conventional intensity image.

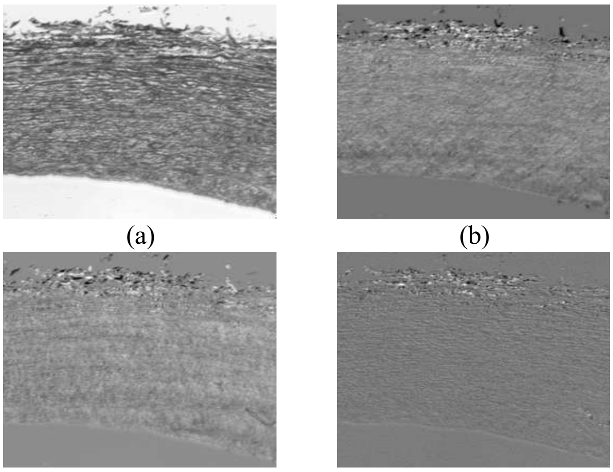
(a) (b)
(c) (d)

Figure 5 – S_0 (a), S_1 (b), S_2(c), and S_3 (d) images of a vessel. The image at the upper left is to be compared with a conventional intensity image.

3. IMAGE CLUSTERING

3.1 Poincaré ball to HSV space mapping

In order to process coherently the physical contents of Stokes images, one needs to handle all the channels at once by the processing algorithms. This can be done by using an adequate mapping of the Poincaré ball to the HSV space and using algorithm devoted to colour image processing. Let us note the normalized Stokes vector as $\bar{\mathbf{S}} = \mathbf{S}/S_0 = \begin{bmatrix} 1 & \bar{S}_1 & \bar{S}_2 & \bar{S}_3 \end{bmatrix}^t$. We define the transformations that map the Poincaré ball to the cylindrical coordinates of the HSV space as follows:

$$H = \tan^{-1}\left(\frac{\bar{S}_2}{\bar{S}_1}\right) \tag{4}$$

$$S = \sqrt{\bar{S}_1^2 + \bar{S}_2^2} \tag{5}$$

$$V = \frac{1}{2} - \frac{\bar{S}_3}{2} \tag{6}$$

Figures (6a-6c) show the mapping result of the normalized Stokes image given in Figure (4). The proposed mapping can be interpreted in the following manner: pixels brightness (V) reflect the handedness of the wave (right to left handedness are represented by dark to bright pixels), the saturation (S) can be interpreted easily the horizontal part of the degree of polarization of the wave DOP while the hue (H) represents the orientation of the polarized fraction of the light.

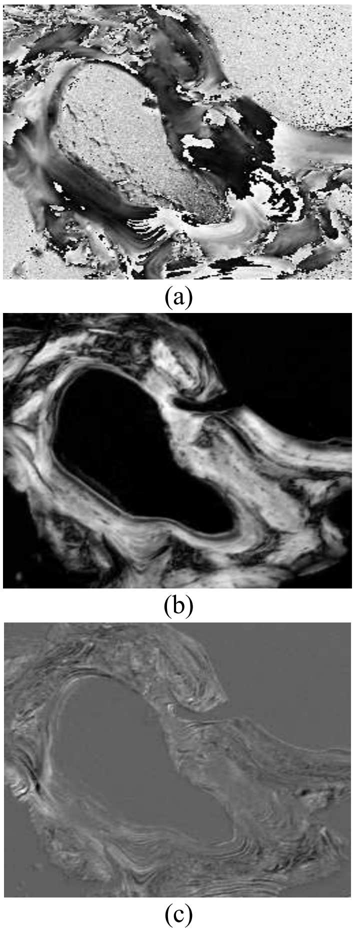
(a)
(b)
(c)

Figure 6 – Resulting HSV channels representation of the normalized Stokes image of the histological section of a bone. (a) H channel, (b) S channel and (c) V channel.

3.2 Polarization-based clustering

The reason for using a clustering process is to classify the pixels of an image into different sets, each set corresponding to a specific physical feature in the imaged scene. Segmentation can prove a difficult task when the physical properties are intricately combined in each pixel location [11], [12]. Then, a coherent processing of the vector features is needed since segmentation based only on scalar values in each channel is almost impossible. Hence we propose a clustering procedure based on a polarization analysis of the scene via the mapping introduced in the preceding section.

Let us have a closer look at equations (4) and (6). We observe that the physical contents of the channels (H) and (V) are independent. Consequently, these two channels can be clustered independently into k classes by using a fuzzy C-means algorithm. We note that the classical Euclidean distance is used when clustering the (V) channel while 1-distance $(dist(H_1,H_2)=|H_1-H_2|)$ is used to cluster the (H) channel, similarly to the segmentation method derived in [13].

At this stage, the membership vectors $\psi_{H,V}$ corresponding to the H and V channels of each pixel (x,y) are obtained and written as:

$$\begin{aligned}\psi_H &= \left(\mu_i^H(x,y)\right)_{i=1,k}\\ \psi_V &= \left(\mu_i^V(x,y)\right)_{i=1,k}\end{aligned} \tag{7}$$

where $\mu_i^{H,V}(x,y)$ represent the membership of the (x,y)'s pixel to the i$^{\text{th}}$-class.

We combine now these values to form a two-dimensional feature vector as follows:

$$\psi(x,y)=\left(\max_{i=1,k}\mu_i^H(x,y),\max_{i=1,k}\mu_i^V(x,y)\right) \tag{8}$$

We apply now the fuzzy C-means clustering algorithm on the above feature vector to obtain the final result for the polarization-based clustering.

Figure (7) shows the 4-classes label map obtained by using the clustering procedure introduced in this paper on the HSV image of Figure (6).

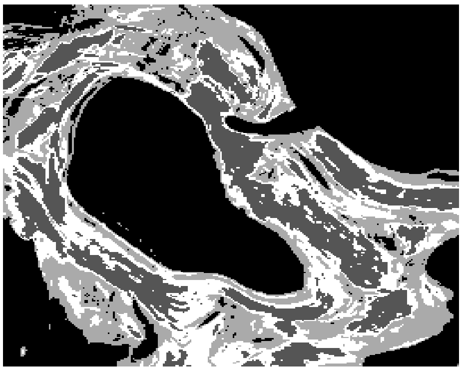

Figure 7 – Label map obtained with our clustering for 4 classes

3.3 Colour preview algorithm

Brightness variations inside each class are not well observed in the V-channel image Figure (6.c) since it reflects the variations over the whole image.

Here we employ a technique that uses the segmentation map obtained by the above-mentioned algorithm as an *a priori* information in order to allow, at best, a distribution of the information in the colour space. This is done by the following way:

Once the label maps are obtained from the above-mentioned algorithm, different masks corresponding to each class (C_k) can be used to extract sets of brightness values from the V-channel image. Histogram equalization is then performed over each set to redistribute uniformly the brightness values inside each class in order to reflect in the best way the intra-class variations. The new brightness values are finally affected to the V-channel. Figure (8) shows the result of the intra-class histogram equalization on the Brightness channel. One can see clearly the advantages of this processing by observing the smooth variation of the information content inside each physical feature represented by different classes as compared to the image in Figure (6.c).

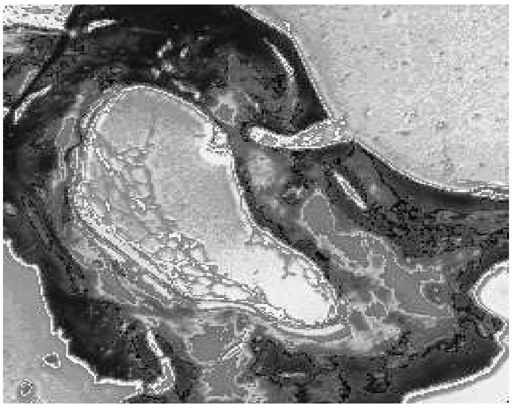

Figure 8 – V-channel image after histogram equalization corresponding to each class

Finally, the three channels H, S, and V can be used to generate an RGB colour image for display purposes. This is presented in Figure (9). The distribution of the colours in the resultant RGB image, is a compact manner to represent the variation of the physical properties of the scene presented previously by four different channels, in one single image. The result of application of the proposed algorithm on the healthy vessel is displayed in Figure (10). Here also we see the smooth distribution of the colors in the RGB resultant image.

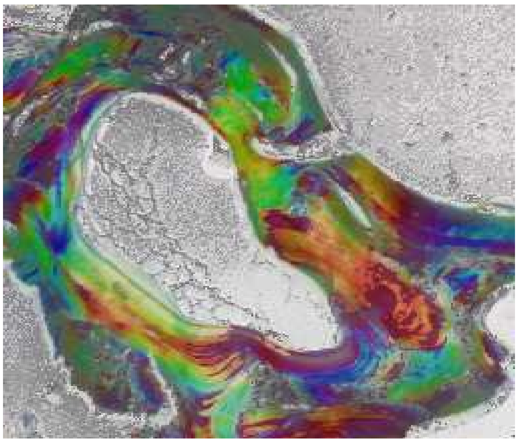

Figure 9 – The combined result of the proposed clustering algorithm with our novel colour preview procedure. The image is for the red picosirius coloured histological section of a bone shown in Figure (4).

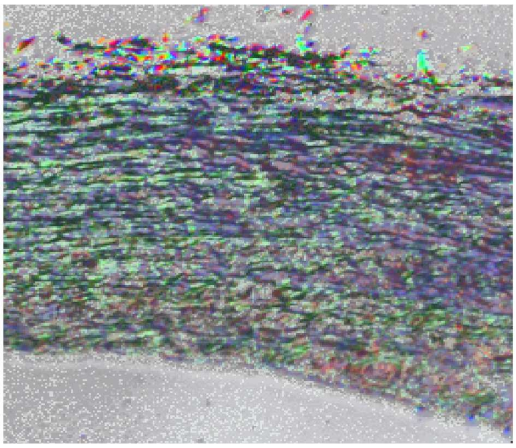

Figure 10 – The combined result of the proposed clustering algorithm with our novel colour preview procedure. The image is a healthy vessel shown in Figure (5).

The whole processing can be summarized as follows:

1. Normalization of the three last channels by the first one.
2. Poincaré ball to HSV mapping
3. Segmentation of the HSV image using the algorithm of section 3.2.
4. Equalization of the histograms corresponding to the pixels of each class in the V channel.
5. Replace of the old V channel by the new one obtained at step 4.
6. HSV image to the RGB image transform
7. Display the RGB image.

4. CONCLUSION

In this paper, we proposed a novel method to cluster efficiently Stokes polarization-encoded images. The proposed approach provides a way to synthesize a maximum of information in a colour preview in the HSV space that permits qualitative interpretation of the target properties in terms of physical contents. The main interest of the method is the use of the segmentation map as an *a priori* knowledge to yield a colouring scheme that preserves the smooth variations of the physical content across the scene. The method was validated on Stokes images of biological tissues and of a healthy vessel, and an illustrative sample is shown here in order to appreciate the interest of the proposed method.

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